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A REVIEW OF SELECTED WORKS ON GUN DYNAMICS

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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This report presents reviews of several selected works on gun dynamics. The reviews are concerned mainly with the applicability of the works to efficient, economical solution of the response of gun tubes to load functions unique to modern gun systems.

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SECTION 1
INTRODUCTION

This report is based upon the review of a number of studies related to gun dynamics; see the Reference section. The works reviewed include reports and books provided by Mr. Alexander Stowell Elder of Ballistics Research Laboratory. In addition, the publication Applied Mechanics Reviews was searched for pertinent papers in the gun dynamics field. This publication, dating from 1948 (Volume 1) to 1981 (Volume 34), reviews the world literature in applied mechanics. Surprisingly, little of direct significance to the gun dynamics field was found, the works contained in Applied Mechanics Reviews being generally treatments which require extensive extrapolation to be applicable to the gun dynamics problem. Similarly, works in other journals, such as the Journal of Applied Mechanics of the American Society of Mechanical Engineers, the Journal of the American Institute of Aeronautics and Astronautics, and the Journal of the Engineering Mechanics Division of the American Society of Civil Engineers, seemingly were void of papers dealing directly with gun dynamics. Apparently, although the technical literature covers a broad range of topics and methods in dynamics, it contains little information that is directly applicable to the gun dynamics - gun pointing accuracy problem. The book by L. Fryba contains a wealth of information on the effects of moving loads on elastic and inelastic solids, elements and parts of structures and on elastic media. Unfortunately, the theory and applications contained therein are directed to slowly moving loads or masses. At high speeds, the Fourier series method employed is inadequate since then a very large number of terms of the series must be retained. Even with the retention of a large number of terms the method is unsatisfactory except for the simplest systems and forcing functions. Hence, it is not applicable to the economical analysis of complex gun dynamics problem.

The successful analysis of a gun dynamics problem depends not only upon the accuracy of the analytical method employed, but also upon the cost of obtaining sufficiently accurate and reliable results. With these objectives in mind, in this report, we emphasize mainly those studies which appear to offer the greatest possibility of achieving accurate modeling of a gun system economically. Accordingly, we consider in some detail the works of P. A. Cox and J. C. Hokanson (Reference 30), T. Feng and T. Hung (Reference 22, page 179), P. C. Parks and C. P[illegible]gan (Reference 26), F. J. Perdreauville (References 13, 14), T. E. Simmons, et al. (References 10, 16, 17, 22, 23, 24, 27), M. T. Soifer and R. S. Becker (Reference 32), and BLM Applied Mechanics Consultants (References 28, 33).

SECTION 2

MUZZLE MOTIONS OF THE M68 105 mm TANK GUN
(P. A. Cox and J. C. Hokanson; Reference 30)

In this work, the mathematical model of the tube consists of two-dimensional beam finite elements. Two degrees of freedom are present at each node, thus permitting a cubic variation in displacement between nodes. The number of elements used is large enough to appear adequate.

Effects considered include initial droop, breech block eccentricity, gas pressure, projectile tube friction force, projectile unbalance, spin, and weight. Sun heating is not included. In addition, the effect of tube motion on projectile acceleration is incorporated.

Vertical motions, horizontal motions and torsion are considered separately. For vertical motions, the agreement between calculated and experimentally measured values is very poor for displacements, velocities and accelerations of the muzzle at projectile exit. The experimentally measured values for velocities, for example, are approximately ten times the calculated values. Some attempts were made to improve the agreement by incorporating nonlinear stiffness in the recoil mechanism. These adjustments were without success.

For horizontal motions, the same program is used, and the agreement between calculated and measured values is somewhat better but still not good.

For torsional motions, the tube is modeled with finite elements having one degree of freedom at each node, allowing a linear variation in angular displacement between nodes. Torsional stiffness of the supports is considered important but must be estimated. Clearances are neglected. The forcing function is due to the projectile spin acceleration. The comparison between experimental and calculated values is similar to that of the horizontal motion case. The calculated angular displacements and velocities are lower than those measured, but the calculated angular accelerations are higher than the measured ones. The authors suggest that improper modeling of the support conditions is primarily responsible for the discrepancies.

In summary, the calculated values of horizontal motion and torsional motion are closer to the measured values (off by a factor of 2 or 3), than are the corresponding values of the vertical motions, which are off by a factor of approximately 100. The calculated values show high frequency oscillations which are not present in the experimentally measured data. This difference could be due to numerical as well as mechanical noise. A stepwise numerical scheme which incorporates a direct integration method of a fairly standard form is used. An improved integration technique, involving some iteration, gives only slightly different results.

In an effort to improve agreement between calculated and measured values, as well as to determine a sensitivity index for various factors, a large number of computer runs were made with various values of the parameters.

Those factors which appear to have an important influence on the results are the motion dependent forces, breech block eccentricity, projectile eccentricity and tube boundary conditions. The importance of breech block eccentricity has been observed by others (Reference 28). Factors which showed little effect are the projectile weight and the breech torque reaction. The inclusion of shear deformation in the tube has a mixed effect on results.

In spite of selecting a wide range of parameters, the authors were unsuccessful in matching experimental and calculated results for motion in the vertical plane. In general, the calculated values of displacements, velocities, etc., are considerably lower than the measured values. No reason for this discrepancy is cited. In the horizontal plane agreement between experimentally and numerically calculated displacement is not good, but is better than in the vertical plane. For the velocities and accelerations in the horizontal plane the agreement is good. In torsion, the agreement between experimentally determined and numerically calculated displacements can be made quite good by adjusting the boundary conditions in the numerical model. Similar comparison for velocities and accelerations, however, do not show such good agreement.

It appears that the finite element model of the gun tube is a good one. However, the modeling of the initial clearance, the recoil mechanism, the support system, and the breech appears to be inadequate. In the latter modeling, there is considerable need for improvement. In addition, the vectorial theory shows that the assumption that the vertical and horizontal displacements of the tube are uncoupled (that is, may be determined independent of one another) is not valid. (See "Dynamics of a Projectile in a Flexible Tube," Interim Report BLM-AMC-81-6, Contract No. DAAK11-80-C-0039, 1 August 1981.) This coupling may account for the discrepancies between calculated and experimentally determined results. Also, overall rigid body motions may account for the larger experimental values.

SECTION 3

TRANSVERSE DYNAMIC RESPONSE OF GUN BARREL WITH TIME-VARYING SUPPORTS
(T. Feng and T. Hung, Reference 22, page 179)

The mathematical basis of the analysis in Reference 22, page 179 is a generalized linear elastic beam equation (Equation 1 in the report) and boundary conditions (Equation 2 in the report), derived by T. Simkins, G. Pflegl, and R. Scanlon (Reference 16).

Equation 1, Reference 22, page 179:

$$
\begin{aligned}
(EIy'')'' + \rho A(x)\ddot{y} = {} & -\rho g A(x)\cos\alpha - p(x,t)a^2 \pi y'' - [V^2 y'' + 2V\dot{y}' + \ddot{y} \\
& + \dot{V}y' + g\cos\alpha]m_p\, \delta(\xi - x) - y'\rho g A(x)(\ddot{X}_0(t)/g - \sin\alpha) \\
& + \int_x^{\ell} y''\rho g A(\bar{x})(\ddot{X}_0(t)/g - \sin\alpha)d\bar{x} + P_1\, \delta(\eta - x) \\
& + P_2\, \delta(\eta + \zeta - x)
\end{aligned}
$$

Equation 2, Reference 22, page 179:

$$y(0,t) = y'(0,t) = 0$$

$$y(\eta,t) = y(\eta + \zeta,t) = 0$$

$$\dot{y}(x,0) = \dot{y}_0$$

$$y(x,0) = y_0$$

where E = modulus of elasticity
I = moment of inertia of the barrel cross-section
ρ = mass density of the barrel
$A(x)$ = cross-sectional area of the barrel
$p(x,t)$ = bore pressure
a = inner radius
V = velocity of the projectile

g = gravitational acceleration

α = inclined angle of the barrel axis

m_p = projectile mass

δ = Dirac delta function

ξ = projectile travel distance

$X(t)$ = recoil and counter-recoil acceleration

ℓ = total length of the barrel

P_1 = reaction of the second support

η = recoil and counter-recoil distance

P_2 = reaction of the third support

ζ = distance between the last two supports

In the right-hand side of Equation (1) of Reference 22, page 179, above, the first term is gravitational force; the second term is Bourdon load; the third term is projectile inertia and gravitational force; the fourth and fifth terms are recoil and counter-recoil inertia forces; and the last two terms are reactions of the supports. Thus, incorporated in the theory are elastic bending of a tapered tube, lateral inertia of the tube, weight of the tube, the Bourdon effect, weight and inertia of the projectile, recoil of the barrel, and lateral constraint from contacting immovable pads. The tube is free to slide axially on the pads. There is no clearance between a pad and the tube. The central axis of the deflected tube is assumed to lie constantly in a fixed vertical plane. The projectile is treated as a point mass. Shear deformation and rotary inertia of the tube are disregarded. Axial friction between the tube and the projectile is disregarded. Although it is not essential to the theory, the gas pressure at any instant is assumed to decrease parabolically from a maximum at the breech to the fraction $(1 + r/2)^{-1}$ of the breech pressure at the projectile, where r is the ratio of the mass of the charge to the mass of the projectile.

In the numerical example that is treated, there are three pad supports idealized as immovable point supports. Initially one pad is at the breech and the other two are at intermediate points between the breech and the muzzle (see Figures 1 and 2 in the report). The system consists of an axially symmetric tube. There is no breech block. The maximum computed displacement and rotation at the muzzle of a 60 mm tube 181 in. long are roughly 0.02 in. and 0.001 radians. These deflections probably would be increased greatly if an eccentric breech block were attached to the tube.

Details of the analysis and the numerical program are not presented in the report. The authors state: "A combination finite-difference, modal analysis, and Picard Iteration scheme is adopted as a basis for the method of solution. Modal analysis is done in a short time interval, considering the location of the barrel supports fixed. The iteration scheme is employed to cope with forcing functions which are response dependent. By revising the modes of the barrel and considering the terminal and initial conditions of the problem, dynamic response is obtained in the next short period of time. Continuing in this way, a successive modal analysis in an iterative manner is established."

"If one assumes that η is constant (i.e., no recoil motion of the barrel), the equations can be solved readily by finite-difference, modal analysis, or any other suitable method. It follows that, for a short period of time, one may attempt to seek an approximate numerical solution by considering η constant. The solution over the whole time interval of concern can be obtained by updating the value of η through successive short time intervals. Furthermore, for a short time interval, the barrel modal functions can be treated as fixed. Using several modal functions to expand the solution in the interval would then result in an approximate solution."

"A difficulty arises in the right-hand side of Equation (1), which involves the unknown transverse loads and must be calculated before the usual modal method can be applied. To overcome this, one may resort to an iterative method. First, one assumes the barrel is under the action of gravitational force, which is a multiple (starting weight factor) of the first term of the right-hand side of Equation (1). The solution of this load gives an amount of deflection which is used to calculate "transverse load" for the next iteration. This is essentially an adaptation of the generalized Picard method. Use of modal analysis in such a manner with a finite-element model has two advantages. It avoids calculating the pad reactions, and it takes account of any attached masses."

A somewhat more general theory than that developed by Feng and Hung is given in Reference 28. In Reference 28, pads are replaced by linear and rotational springs and dashpots. Also, the recoil mechanism is represented by springs and dashpots, and axial friction between the projectile and the barrel is included. A strong effect of eccentricity of the breech block is indicated by numerical computations.

Numerical results based upon the work of Reference 22 is questionable since the projectile is treated as a point mass, axial friction between the tube and projectile is disregarded, and coupling between vertical and horizontal tube motions is not included.

SECTION 4

EXPLANATORY NOTES FOR THE BARREL VIBRATION PROGRAM FLEX
(P. C. Parks and G. Pagan, Reference 26)

In Reference 26, the gun under consideration is mounted on a tank, which is a moving non-Galilean reference frame. It would be very helpful to have a diagram illustrating the notations. The barrel is flexible, but it is assumed to deflect only in a fixed vertical plane. Gyroscopic action of the projectile is not considered. The "shot" which consists of the charge and the projectile, is conceived to be distributed along the barrel, rather than being concentrated at the projectile. The total mass of the shot is M, and the mass of shot per unit length of the barrel is defined to be Mf(x), in which x is an axial coordinate along the barrel.

The mathematical basis of the analysis is Equation (2.1) of Reference 26.

<u>Equation (2.1), Reference 26:</u>

$$\frac{\partial^2}{\partial x^2}\left[EI(x)\frac{\partial^2 y}{\partial x^2}\right] - a_B(t)\left[\int_x^{\ell} m(x)dx\right]\left[\frac{\partial^2 y}{\partial x^2} + \frac{\partial^2 y_0}{\partial x^2}\right] + a_B(t)m(x)\left[\frac{\partial y}{\partial x}\right.$$

$$\left. + \frac{\partial y_0}{\partial x}\right] + m(x)\frac{\partial^2 y}{\partial t^2} = \sum_{i=1}^{3} F_i$$

where

$$F_1 = -Mf(x)\left[\frac{\partial^2 y}{\partial t^2} + 2V_s\left(\frac{\partial^2 y}{\partial x \partial t} + \dot{\theta}_c\right) + V_s^{\,2}\left(\frac{\partial^2 y}{\partial x^2} + \frac{\partial^2 y_0}{\partial x^2}\right) + g\right]$$

$$F_2 = -(Mf(x) + m(x))\left[(x - X)\ddot{\theta}_c - 2V_B\dot{\theta}_c + \ddot{Z}\right]$$

$$F_3 = MF(x)(V_s R)^2\delta_2 \sin\left[(X_{st} - X_s)R + \varepsilon\right]$$

The Bourdon effect should introduce a term $\frac{1}{4}\pi d^2 p y_{xx}$, where y is the deflection, d is the bore diameter, p is the gas pressure, and $y_{xx} = \partial^2 y/\partial x^2$. No such term appears in Equation (2.1) of Reference 26. Apparently, the Bourdon effect is neglected. Also, axial friction of the projectile on the barrel is disregarded. The absolute deflection D is represented by Equation (2.2) of Reference 26, namely

Equation (2.2), Reference 26:

$$D = y(x,t) + (x - X)\theta_c + Z$$

where y(x,t) is the deflection measured from the static configuration, X is the distance from the trunnion to the center of the rear bearing, θ_c is the angular displacement of the cradle, and Z is the displacement of the trunnion. The authors state: "It must be noted that y is the displacement measured from the locus of centers of gravity (i.e., centroids) of each cross section area of the barrel as it droops naturally under gravity, having any manufacturing bore asymmetries that we want to consider." However, the asymmetries are assumed to be due solely to vertical misalignment of the bore. Sidewise misalignment would rotate the principal axes of inertia of the cross sections and cause sidewise bending. It seems that manufacturing inaccuracies would be very unlikely to produce a barrel whose centroidal axis would lie in a vertical plane. Consequently, an initially straight barrel with a centered bore is considered in the following discussion. For simplicity, the total deflection is denoted by y(x,t), although the authors separate it into a sum $y + y_0$, where y_0 is the static deflection.

The differential equations of beams can be derived by specialization of the differential equations of shells. This derivation is carried out for curved beams in "Foundations of Practical Shell Analysis" (FPSA), Department of Theoretical and Applied Mechanics, University of Illinois, Revised Ed. 1964, Art. 48. The differential equations of equilibrium (Equation 261, FPSA) apply for initially curved beams and straight beams, where, for precision, 1/R is the curvature of the bent centroidal axis. Consequently, if s is arc length on the bent centroidal axis,

$$-\frac{\partial^2 M}{\partial s^2} + \frac{N}{R} + q = 0 \tag{4.1}$$

in which M is the bending moment, N is the tension in the beam, and q is the distributed normal load (Figure 4.1).

If the beam is initially straight, classical beam theory yields

$$M = \frac{EI}{R} \tag{4.2}$$

Consequently, by Equation (4.1),

$$\frac{\partial^2}{\partial s^2}\left(\frac{EI}{R}\right) - \frac{N}{R} - q = 0 \tag{4.3}$$

Equation (4.3) applies for a slender straight elastic beam with any symmetrical cross-sectional shape. For a freely vibrating beam, q is an inertial load.

Since the gun is mounted on a tank, it is necessary to determine q(x,t) for a non-Galilean reference frame. Let (x,y) be a coordinate system that moves in a fixed (Galilean) reference frame (ξ,η) (Figure 4.2). The motion of frame (x,y) is determined by

$$\xi_0 = \xi_0(t) \ , \ \eta_0 = \eta_0(t) \ , \ \theta = \theta(t)$$

Let the gun tube be referred to the (x,y) system. The instantaneous form of the axis of the tube is given by x = x(s,t), y = y(s,t), where s is arc length along the axis of the tube. The projectile is located at the point s = s(t). Reference is made to "Dynamics of a Projectile in a Flexible Tube" (DPFT), BLM Applied Mechanics Consultants, Interim Report 81-6, Contract DAAK-11-80-C-0039, U.S. Army ARADCOM, BRL, Aberdeen Proving Ground, Maryland, 21005.

By Equation (18) of DPFT,

$$\frac{1}{R} = x_s\, y_{ss} - y_s\, x_{ss} \tag{4.4}$$

where subscript s denotes the partial derivative. By Figure 4.2

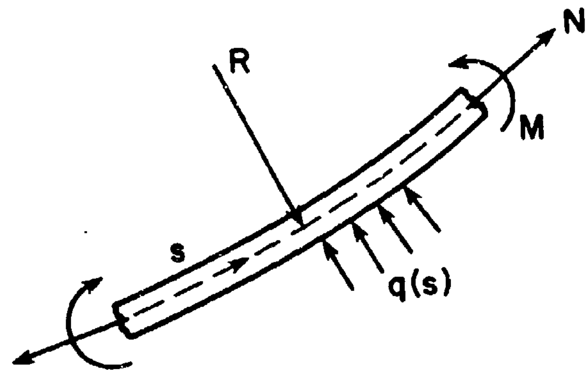

Figure 4.1. Element of Beam

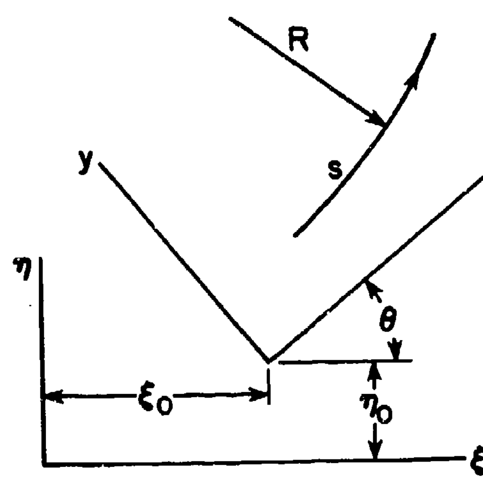

Figure 4.2. Coordinate System

$$\xi = \xi_0 + x \cos \theta - y \sin \theta$$

$$\eta = \eta_0 + x \sin \theta + y \cos \theta \tag{4.5}$$

Consequently,

$$\frac{1}{R} = x_s \, y_{ss} - y_s \, x_{ss} = \xi_s \, \eta_{ss} - \eta_s \, \xi_{ss} \tag{4.6}$$

Accordingly, $\frac{1}{R}$ is invariant under a coordinate transformation as should be expected.

By Equation (21) of DPFT, the tangential and normal components of the acceleration of the center of mass of the projectile are

$$a_t = \ddot{s} + \xi_s \, \xi_{tt} + \eta_s \, \eta_{tt}$$

$$a_n = \dot{s}^2(\xi_s \, \eta_{ss} - \eta_s \, \xi_{ss}) + (\xi_s \, \eta_{tt} - \eta_s \, \xi_{tt}) + 2\dot{s}(\xi_s \, \eta_{st} - \eta_s \, \xi_{st}) \tag{4.7}$$

Substituting Equation (4.5) into Equation (4.7) we get, after rather laborious algebraic reductions,

$$\begin{aligned} a_t = {} & \ddot{s} + \ddot{\xi}_0(x_s \cos \theta - y_s \sin \theta) + \ddot{\eta}_0(x_s \sin \theta + y_s \cos \theta) \\ & + (x_s \, x_{tt} + y_s \, y_{tt}) + 2\dot{\theta}(x_t \, y_s - x_s \, y_t) + \ddot{\theta}(xy_s - yx_s) \\ & - \dot{\theta}^2(xx_s + yy_s) \end{aligned} \tag{4.8}$$

$$\begin{aligned} a_n = {} & -\ddot{\xi}_0(x_s \sin \theta + y_s \cos \theta) + \ddot{\eta}_0(x_s \cos \theta - y_s \sin \theta) \\ & + (x_s \, y_{tt} - y_s \, x_{tt}) + 2\dot{\theta}(x_s \, x_t + y_s \, y_t) + \dot{\theta}^2(xy_s - yx_s) \end{aligned}$$

$$+ \ddot{\theta}(xx_s + yy_s) + 2\dot{s}[x_s\, y_{st} - y_s\, x_{st} + \dot{\theta}(x_s^{\,2} + y_s^{\,2})]$$

$$+ \dot{s}^2(x_s\, y_{ss} - y_s\, x_{ss}) \tag{4.9}$$

Equations (4.8) and (4.9) give the tangential and normal components of the absolute acceleration of the projectile. The acceleration of the cross section of the barrel at the point where the projectile lies is obtained by setting $\dot{s} = \ddot{s} = 0$ in Equations (4.8) and (4.9), since the cross section does not move with respect to the tube. Accordingly, regarding s and t as independent variables, we obtain the acceleration of any point on the axis of the tube from Equations (4.8) and (4.9).

The distributed inertial load transverse to the tube is $q = -ma_n$, where $m(x)$ is the mass of the tube per unit length. The mass distribution of gas in the tube at a particular instant may be included in m. Equations (4.3), (4.4) and (4.9) yield

$$\frac{\partial^2}{\partial s^2}[EI(x_s\, y_{ss} - y_s\, x_{ss})] - N(x_s\, y_{ss} - y_s\, x_{ss})$$

$$- m\ddot{\xi}_0(x_s \sin\theta + y_s \cos\theta) + m\ddot{\eta}_0(x_s \cos\theta - y_s \sin\theta)$$

$$+ m(x_s\, y_{tt} - y_s\, x_{tt}) + 2m\dot{\theta}(x_s\, x_t + y_s y_t)$$

$$+ m\dot{\theta}^2(xy_s - yx_s) + m\ddot{\theta}(xx_s + yy_s) = 0 \tag{4.10}$$

A term representing the gravitational load should be appended to Equation (4.10).

For correlation with the work of Parks and Pagan, we set $\theta = 0$, $\ddot{\eta}_0 = 0$, and $\ddot{\xi}_0 = -a_B$. Also, because of inextensionality of the center line, $x_t \approx -V_B$, $x_{tt} \approx -a_B$ where V_B and a_B are the axial velocity and acceleration of the barrel due to recoil. The tension N results from acceleration of the part of the barrel beyond section x. Consequently,

$$N = a_B \int_x^{\ell} m dx \tag{4.11}$$

Also, the approximation $s = x$ is used. Accordingly, Equation (4.10) is approximated by

$$\frac{\partial^2}{\partial s^2}(EIy_{xx}) - a_B\, y_{xx} \int_x^{\ell} m dx + m\, y_{tt} + 2ma_B\, y_x + 2m\dot{\theta}(y_x\, y_t - V_B)$$

$$+ m\dot{\theta}^2(x\, y_x - y) + m\ddot{\theta}(x + yy_x) = 0 \tag{4.12}$$

It is not possible to compare Equation (4.12) with Equation (2.1) of Reference 26 in detail, since the notations in the report require elaboration and clarification. However, there appear to be some discrepancies. The term $\partial^2 y/\partial x\, \partial t$ in the expression for F_1 is puzzling. In Equation (4.9), it occurs only in the expression with the factor s, and this expression drops out of the load term q. Likewise the derivative $\partial^2 y/\partial x^2$ seemingly should not occur in the expression for F_1. On the other hand, there should be a term with factor $\dot{\theta}^2$, unless it is considered negligible. Equation (4.12) indicates that the term $ma_B\, y_x$ in Equation (2.1) of Reference 26 should be multiplied by 2. The differences between Equation (2.1) of Reference 26 and Equation (4.12) raise the suspicion that all is not right. It might be suspected that discrepancies occur because rotary inertia and shear deformation are not included in Equation (4.12), but Parks and Pagan state that they use the Euler-Bernoulli theory of beams. If PROGRAM FLEX is to be used, a thorough scrutiny of its mathematical basis is advisable, in view of the questions raised above.

SECTION 5

ANALYSIS OF THE LATERAL MOTION OF AN UNBALANCED PROJECTILE IN A RIGID GUN TUBE
(Farrell J. Perdreauville, Reference 13)

The report is essentially a presentation of the Euler theory of dynamics of a rigid body in a Galilean reference frame. The Euler equations for the moments (Equation 1 of Reference 13) are stated in a general form that applies when the body-centered coordinates (x, y, z) do not necessarily coincide with principal axes of inertia of the projectile. For gun dynamics, the freedom to choose the axes (x, y, z) arbitrarily has some advantages. However, the moment $\overline{M}$ that acts on the projectile ordinarily is determined with respect to gun-based coordinates, so a transformation to the body-centered coordinates of the projectile is needed in any case. This transformation is given by Equation (11) of Reference 13. It is to be noted that these equations specify M_x, M_y, M_z as functions of the Euler angles (G, A, θ) and the time t, provided that the moments M_X, M_Y, M_Z about the gun-based axes are known functions of t.

The Euler angles (G, A, θ) are not exactly the conventional ones. To correlate them with the usual Euler angles (θ, ϕ, ψ), the following change of notations is required:

$$A \rightarrow \frac{1}{2}\pi - \phi, \quad G \rightarrow \theta - \frac{1}{2}\pi, \quad \theta \rightarrow -\psi$$

Equation (4) expresses the angular velocity components (ω_x, ω_y, ω_z) in terms of the Euler angles and their time derivatives. Since these equations are purely kinematical, they are valid for arbitrary orthogonal axes (1, 2, 3). By means of Equation (4) of Reference 13, ω_x, ω_y, ω_z are eliminated, and coupled second-order, nonlinear differential equations are obtained. They theoretically determine (G, A, θ) as functions of t, if the moments (M_X, M_Y, M_Z) and the initial conditions are given. Reference is made to another report (SC-RR-710071) for the functions (M_X, M_Y, M_Z). In the case of a balloting projectile, continuity of these functions is questionable, since the vector $\overline{M}$ derives partly from impacting of the projectile on the wall of the tube. If G, A, θ are known functions of t, Equations (1) and (4) of Reference 13 determine M_x, M_y, M_z. These results apply for a rigid immovable gun. The theory provides only the moments on the projectile; it does not provide the forces.

The Euler angles (θ, ϕ, ψ), regarded as generalized coordinates, have a singularity at the pole, $\theta = 0$, since the longitude ϕ is indeterminate at that point. From a computational standpoint, equations involving the Euler angles are poorly conditioned if the colatitude θ is small. Therefore, the Euler angles are unsuitable coordinates for studying small oscillations in a neighborhood of the polar axis. This circumstance may cause trouble if the present theory is programmed for a computer.

SECTION 6

ANALYSIS OF THE LATERAL MOTION OF AN UNBALANCED PROJECTILE IN AN ELASTIC GUN TUBE

(Farrell J. Perdreauville, Reference 14)

The report is divided into three parts. The first part treats the motion of a rigid projectile that is subjected to prescribed forces and moments. This theory is based on Newton's second law and Euler's dynamical equations for a rigid body. The generalized coordinates are the rectangular coordinates of the center of mass of the projectile and the Euler angles. The Euler equations are presented in a general form that applies when the body-centered coordinates in the projectile do not necessarily coincide with the principal axes of inertia of the projectile. Since the deflection of the tube does not enter explicitly into consideration in the first part of the report, the theory in that part is virtually the same as that presented by the author in his earlier analysis of the motion of a balloting projectile in a rigid gun tube (see Section 5 and Reference 13).

The second part of the report treats the deflection of the tube under the action of a distributed time-dependent load $p(x,t)$. The analysis is restricted to the case in which the tube is cantilevered from a rigid immovable abutment. Also, the tube is taken to be uniform; i.e., there is no taper. Vertical and sidewise deflections are considered to be uncoupled. Consequently, only one component of deflection (e.g., the vertical one) need be considered here.

The deflection is represented in the form,

$$W = \Sigma\phi_n(x)\ q_n(t)$$

in which the functions $\phi_n(x)$ are natural modes of a uniform cantilever beam. The differential equation of motion is

$$EI\ W_{xxxx} + m\ W_{tt} = p(x,t)$$

Hence,

$$EI\Sigma\phi_n''''\ q_n + m\Sigma\phi_n\ \ddot{q}_n = \Sigma p_n(t)\ \phi_n(x)$$

in which $p_n(t)$ is a coefficient in the expansion of $p(x,t)$ in a series of natural modes ϕ_n. According to the theory of free vibrations of a uniform beam, $\phi_n'''' = \beta_n^4 \phi_n$, where β_n is an eigenvalue. Consequently,

$$\ddot{q}_n + \frac{EI\beta_n^4}{m} q_n = \frac{p_n(t)}{m}$$

With the initial conditions, this differential equation determines the functions $q_n(t)$. Accordingly, the deflection $W(x,t)$, corresponding to the load distribution $p(x,t)$, is formally determined.

The third part of the report is concerned with conditions of consistent displacement of the projectile and the tube. A projectile with a slip ring is considered. Balloting is contemplated. The bourrelet does not necessarily touch the bore. The author considers the force on the bourrelet when contact is established. Motion of the projectile down the bore is considered to be specified. The spin moment is computed from the specified spin acceleration. The general pattern of the compatibility relations for the projectile and the tube is considered, but some details are omitted. The author states: "This report indicates the formulation by which forces and moments are included in the equations of motion. The amount of detail that is included in balloting analyses will vary, depending on relative magnitudes of various phenomena and the required accuracy. The analysis should lend itself to simplification, as well as a building-block sequence of adding detail as one becomes more familiar with its use."

The force that the projectile exerts on the tube is conceived to be distributed, since it is represented by $p(x,t)$. Actually, forces of contact between the projectile and the bore are concentrated at the slip ring and the bourrelet. This circumstance should cause no trouble, however, since Dirac delta functions, representing the concentrated forces, can be expanded in series of natural modes of the tube. The Bourdon effect and other effects of gas pressure in the tube are disregarded.

The practical value of the theory appears to be limited because the tube is considered to be completely fixed at the breech, and the outside diameter of the tube is taken to be a constant. Clamping of the tube at the breech precludes recoil phenomena. Although the recoil displacement is small while the projectile is in the tube, it causes an angular jerk if the center of mass of the breech is offset from the axis of the tube. Numerical studies of a simplified system, in which the projectile is represented as a point mass, have shown that this effect has a deleterious influence on accuracy of firing. (Reference 28)

There are two well-proven ways to reduce the tube and the projectile to a system with finite degrees of freedom. One way is the method that is used in the present report; namely, expansion of the deflection of the tube in a truncated series of natural modes. The other way is the use of finite-element approximations. The latter method is better suited for treating taper of the barrel, tuning masses, multiple supports, and complicated boundary conditions at the breech. With either method, the motion can be analyzed by means of Lagrange's equations. There is some truth in Lagrange's boast: "The methods that I expound require neither constructions nor geometrical nor mechanical reasoning, but only algebraic operations, subject to an exact and invariable procedure." It appears that some of the complex interactions between the projectile and the tube can be evaded by using the Lagrangian method. If the forces and moments deriving from contact between the projectile and the bore are desired, they can be calculated readily by Newton's laws and Euler's equations after the motion is determined. It seems inevitable that balloting causes serious complications, because intermittent rubbing of the projectile on the wall of the tube causes discontinuities in the constraining forces and moments.

SECTION 7

DYNAMIC ANALYSIS OF THE 75mm ADMAG GUN SYSTEM

(Martin T. Soifer and Robert S. Becker, Reference 32)

This report represents a lumped-parameter model of the gun system, consisting of springs and lumped masses. This method has been widely used for structural analysis, but it has been largely superseded by finite-element methods employing piecewise polynomial approximations (usually piecewise cubics).

The gun tube and supporting parts are treated as elastic beams for stiffness purposes. Bending, shear, axial and torsional stiffnesses are included. Nineteen mass points are selected with six Degrees of Freedom (D.O.F.) at each mass point to produce a 114 D.O.F. system. The representation of each element as a rigid body with six degrees of freedom is realistic, provided the mass points are selected appropriately.

Because of the large number of D.O.F. of the model, there are many coefficients (both stiffnesses and inertias) which must be determined. One would anticipate considerable difficulty in obtaining realistic values for them. Detailed instructions for the accurate determination of all these coefficients are lacking.

It appears that 114 D.O.F. is too large a number to be handled economically for the full range of numerical integration that is presumably required to describe a round. One should be able to model the more important characteristics of the gun motion by a much simpler system containing a considerably reduced number of D.O.F. In particular, after the most significant behavior of the gun system has been satisfactorily represented, finer tuning of the model may be accomplished later by a more complex model.

The result that calculated natural frequencies of the gun system are bunched seems suspicious, but it is physically possible. In fact, multiple roots of the frequency equation can occur. These multiple roots can be eliminated by small changes in the system (e.g., spring constants or masses). Then bunching of the frequencies would occur.

The assumption concerning the applied and induced forces and moments during firing are suspect, particularly, the discarding of moments due to breech eccentricities and the treating of the projectile as a point mass.

The tremendous amount of input data required and the large number of degrees of freedom employed (with required stiffness and mass data) appear to render this approach economically (and perhaps, practically) unsound.

SECTION 8

GUN DYNAMICS STUDIES OF T. E. SIMKINS AND COWORKERS

(References 10, 16, 17, 22; pages 81-146, 373-469, 23, 24; pages 166-177, 27)

A broad range of studies has been undertaken by T. E. Simkins and his coworkers. In Reference 10 four hundred documents were surveyed, covering dynamics, vibrations, stress, heat transfer, reliability, and math-modeling. The objective, as of March 1973, was to establish an up-to-date knowledge of existing computer models of automatic weapons. Some of the conclusions reached in March 1973 still are applicable today. For example, on page 62, a partial summary of Vibrations states "There has been considerable work done on the mathematical modeling of weapons, however, the actual models are very particular in nature and it is therefore impossible and perhaps unreasonable to attempt to apply these models to predict the motion of an as yet unconstructed system. Many large computer codes have been developed recently to formulate and solve the ordinary differential equations. The study has also shown that certain physical phenomena such as material and structural damping and friction are not completely understood." On pages 84 and 85, the summary and recommendations on the literature on Stress Analysis included the following remarks: "2. The extent of a desired math model should be decided on. If only a math model of the barrel is required, a version of one of the intermediate computer codes altered to include other desired analyses should suffice. If one wishes to consider weapon components, also, then a general-type computer code must be developed. If one desires to have the dynamic loading situation of a pulse traveling down the barrel (or more realistically, giving this pulse the mass of the projectile), a general computer code would probably be required even for the barrel. In addition to stress analysis, heat transfer, etc., the possibility of including an optimization process for reducing weight, maximizing firing rate, etc., must be considered.

3. A study should be made on how to present the above work in the form suitable for use by designers or to decide the level at which it can be used for design purposes.

The scope of this task was to evaluate math models for automatic weapons. None were found but there exists a substantial body of work which can be used in this area and it was this work that was reported on."

On page 152, the Recommendations section states "In the future we would recommend that model development proceed only after a phase of thorough planning. Such planning must include strict definition of the purpose of the model, i.e. exactly what questions will the model be expected to answer? The tendency has been, in the past, to ignore inevitable obstacles or impracticalities. This tendency must be resisted. Sooner or later the weak links in a modeling effort must be faced. In some cases the weakness may be in the area of soils modeling or the modeling of an attached structure - or it may imply imprecise knowledge of friction or forces of impact. In any cases these prospects must be faced in the planning stage rather than be hand-waved aside as they are encountered later on. A preliminary assessment of the effect of model weaknesses on the service desired of the model must be a part of the planning process. For example, if a model is expected to predict gun pointing direction within one-mil accuracy, then unless the weapon is mounted upon a seismic block, ordinary mounting conditions alone are certain to spoil the intended predictions." And on page 153, "The previous paragraphs assume that a complete model of a weapons system is sought. Serious thought should be given, however, to the possible utility of an incomplete systems model; i.e. a subsystem model composed only of those portions of a weapons system which can be represented accurately by deterministic models. Such models may prove useful for analysis in certain disciplines such as stress and heat-transfer analysis." A remark is also made to the effect, page 153, that the organizational success and international acceptance of NASTRAN, a large finite element code, gives it a lead position among potential candidates for a basic code from which special adaptions can proceed. Although the present author agrees with the previously quoted recommendations, he does not endorse the employment of a large general use computer code, such as NASTRAN, as the basis for the solution of the rather specialized problem of gun dynamics (gun pointing accuracy).

Accurate summaries of the results of References 16 and 17 have been given by A. S. Elder, Reference 22, pages 1-26. As noted by Elder, the authors of Reference 16 employed NASTRAN as the main computational tool to calculate transient motion of the M113 gun tube. Included in the study of Reference 16 were the effects of tube droop, gas pressure and axial inertia of the barrel, as well as the "Bourdon" effect. The effects of a moving mass were considered in Reference 17. The effects of the moving mass are significant, but not dominating. In Reference 17, the feasibility of handling problems of projectile/bore interaction via the method of finite elements is examined. The general procedure is applied to the motion of a uniform elastic beam with a point mass traveling on it. The beam is divided into several segments, and each segment is regarded as a short beam. Continuity of deflections and slopes is imposed. Accordingly, a piecewise cubic approximation is used.

The principal objective of Reference 17 is to investigate the feasibility of the finite-element method for more complicated gun-tube problems. The present author believes that the finite-element method can be a useful tool if the modeling of the system is accurate. For a simple beam, Simkins obtains very close agreement between the finite-element solution and an analytical solution by Ayre and Jacobsen (Reference 2 of Simkins' report, i.e., of Reference 17).

In Reference 22, pages 81-146, Simkins studies the possibility of parametric resonance in gun tubes. Following an instructive preliminary discussion of parametric excitation, which is elaborated in treatises on nonlinear mechanics (e.g., N. Minorski, Introduction to Nonlinear Mechanics, J. Edwards, Ann Arbor, Mich., 1947), the author concentrates on the motion of a uniform elastic beam, mounted as shown in Figure 8.1. The problem is reduced to one of ordinary nonlinear differential equations with independent variable t by an expansion of the axial displacement U in a cosine series and an expansion of the lateral deflection v in a series of natural modes of a

Figure 8.1. Uniform Elastic Beam

cantilever. Coupling between axial and transverse displacements is incorporated in the equations.

Single-round and multiple-round resonance are studied. NASTRAN is used. The phrase "single-round resonance" is perhaps misleading. In the case of a single round, an initial-value problem is encountered. Under certain conditions, it may have a solution that increases exponentially over a short period. Multiple rounds, with a suitable period, may cause resonance in the usual sense. The importance of this phenomenon in gun dynamics problems is questionable.

In Reference 22, pages 373-469, Simkins again employs the NASTRAN code, this time to study the radial and transverse response of gun tubes by finite element methods. Previous work published by the author (e.g., References 16 and 17) is reviewed treating several problems associated with in-bore ballistics and a limited comparison with experimental work accomplished more recently is given.

One problem concerns the radial response of a tube bore produced by a traveling ballistic pressure. Computational results (obtained via NASTRAN) show good correlation with BRL experimental results obtained for the 175 mm M113 gun tube, even though the NASTRAN model employed trapezoidal axisymmetric ring elements, and hence, is restricted to axisymmetric applied loads and deformations.

The computational model employed an integration time step small enough to predict vibration response as high as 20 khz. Unfortunately an inordinate amount of computer time is required for such time steps, particularly since a 250 degree of freedom model was employed (which the author considered somewhat limited).

A systematic derivation of the governing transverse tube motions is given, incorporating the most comprehensive up to date load set available (see also Reference 17). It includes all the effects noted in the discussion of Reference 17. Coupling between vertical and horizontal motion is not included, since the projectile is treated as a mass point (see Reference 33).

A comprehensive discussion of the state of the art in moving mass problems is presented. It includes an example of the response of a uniform, simply supported beam subjected to a concentrated mass moving along the beam at a <u>constant</u> velocity under the effects of gravity (see Reference 17). A succinct, but clear, discussion of the theoretical differences between the moving force problem and the moving mass problem is presented.

In Reference 23, the authors emphasize that curvature-induced loads should be included in any theory of gun tube motion during firing. The work follows closely that of References 16 and 17 and pages 373-469 of Reference 22. In the first section of Reference 23, the authors observe that contrary to popular belief dynamic bore expansions during the interior ballistic cycle create significantly higher tube wall stresses than those on which the tube design is based, namely those stresses calculated by the classical Lame formula which is generally viewed as a conservative design criterion (see Reference 17). In the second part of Reference 23, the authors show that transient bending vibrations may arise during firing due to tube curvature, which produce muzzle motions of sufficiently large magnitude to explain a part of the error at the target. Following the development of Reference 17, three sources of tube curvature are derived, namely, that due to recoil loads, that due to "Bourdon" load, and that due to projectile loads. The effects of recoil and Bourdon loads are treated in some detail. Highly detailed tube geometries and interior ballistic curves of pressure and projectile motion for specific weapons (e.g., the 175 mm M113 gun tube and th^ 105 mm M-68 gun tube) have been included in the analysis. The NASTRAN c. is again used, although special programming is required for the cu ture-induced load functions. The authors conclude that tube curvature is an important effect in gun-pointing accuracy problems.

In Reference 24, pages I-66 through I-77, the results of the second part o. Reference 23 are again presented for the 105 mm M-68 gun tube.

SECTION 9
CONCLUSIONS

The works discussed in Sections 2, 4, 7 and 8 appear to form the most suitable basis for a gun pointing accuracy program. Of these works, the work of Parks and Pagan (Section 4) appears to have certain technical errors of omission, and it should be used with caution. The work of Soifer and Becker appears to have considerable difficulty in economical and technical application. This work is a lumped-mass study which has been largely superseded by the finite-element method. Simkins and his associates have studied a wide range of effects (Section 8). However, the use of NASTRAN, a general computer code, is very expensive and for the highly specialized loading functions of gun dynamics problems requires special programming.

The work of Cox and Hokanson, which is similar in part to earlier work done by BLM Applied Mechanics Consultants (Reference 28), appears to have considerable merit, even though there are wide differences in values calculated by Cox and Hokanson and values experimentally measured. The finite-element model of the gun tube employed by Cox and Hokanson appears to be a good one. In the opinion of the present author, the concept of a computer program designed explicitly for the gun dynamics problem is a valid one, since the gun dynamics problem (loading functions, etc.) is a highly specialized one, requiring very careful attention to the detailed modeling of the gun system.

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